# Booster Corrector System Specification

*Eric Prebys, Jim Lackey, David- Harding, Craig Drennan*

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**FIGURES AND TABLES**

# I. Introduction

This is a revision of the original Booster Corrector System Specifications dated 3 November 2004. This document reflects the adjustments that have been recommended to the field strengths and slew rates. It also includes the parameters of a prototype magnet package that is very nearly completed and is expected to be available in May of 2006. From the magnet field requirements and the estimated parameters of the various magnets in the package, power supply requirements are derived and presented here also.

# II. Existing System

The Fermilab Booster includes corrector packages in each of the 48 sub periods. Each corrector package includes:

- Horizontal trim
- Vertical trim
- Quadrupole
- Skew Quadrupole

The dipole trim for which the sub period in question is a high-beta region has a ramped controller, while the other one has a DC setting. That is

- Short straights: Horizontal ramped, Vertical DC
- Long straights: Vertical ramped, Horizontal DC

Each type of quadrupole has an individual DC offset to which is added a ramped current common to one quarter of the ring (although operationally, all four quadrants have identical ramps).

The existing system cannot be run hard enough to adequately control beam position or tune through the cycle without overheating.

The sextupoles are in separate packages. They are bussed in two families with different magnet designs, 12 horizontal sextupoles (SEXTS) and 9 vertical sextupoles (SEXTL). Consolidating them in the same package with the other trims would free up space for other devices, but more importantly it would allow control of resonances that the current concentration of magnets cannot touch.

# III. Beam Control Requirements

## III.1 Position

Figure III.1.1 shows the beam position at all points around the ring, at roughly 5 millisecond intervals throughout the acceleration relative to the position at injection. Because the tuned injection orbit represents the optimum beam position, this plot would ideally be flat. Unfortunately the existing corrector system is only capable of moving the beam a few millimeters at high field. Figure III.1.2 shows one of the most extreme cases of motion throughout the cycle.

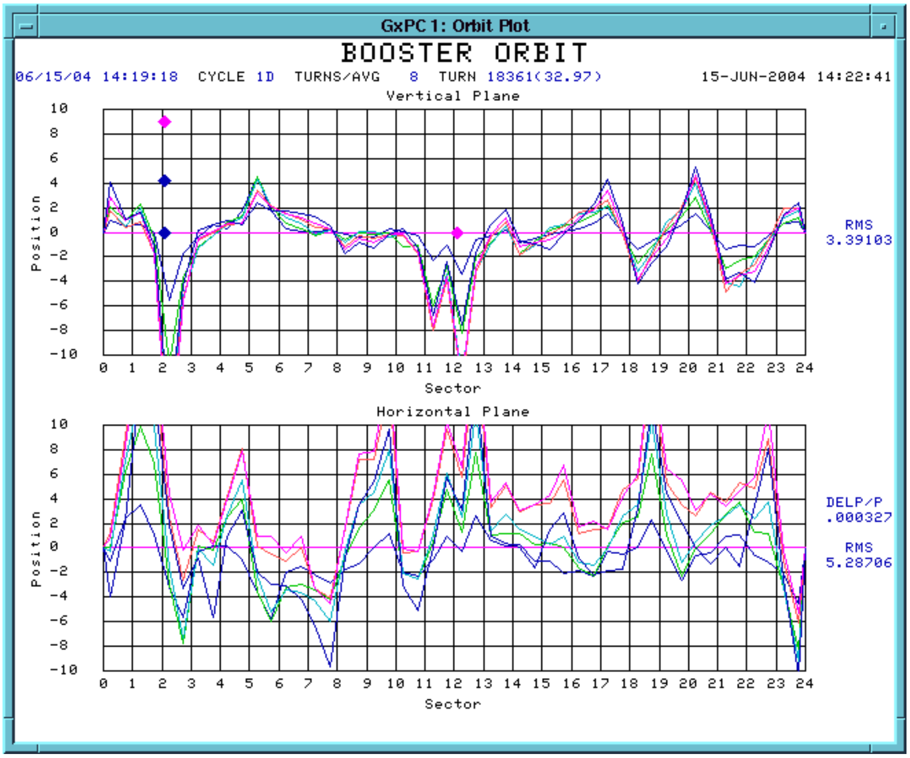



Fig. III.1.1 Beam position around the ring relative to position at injection

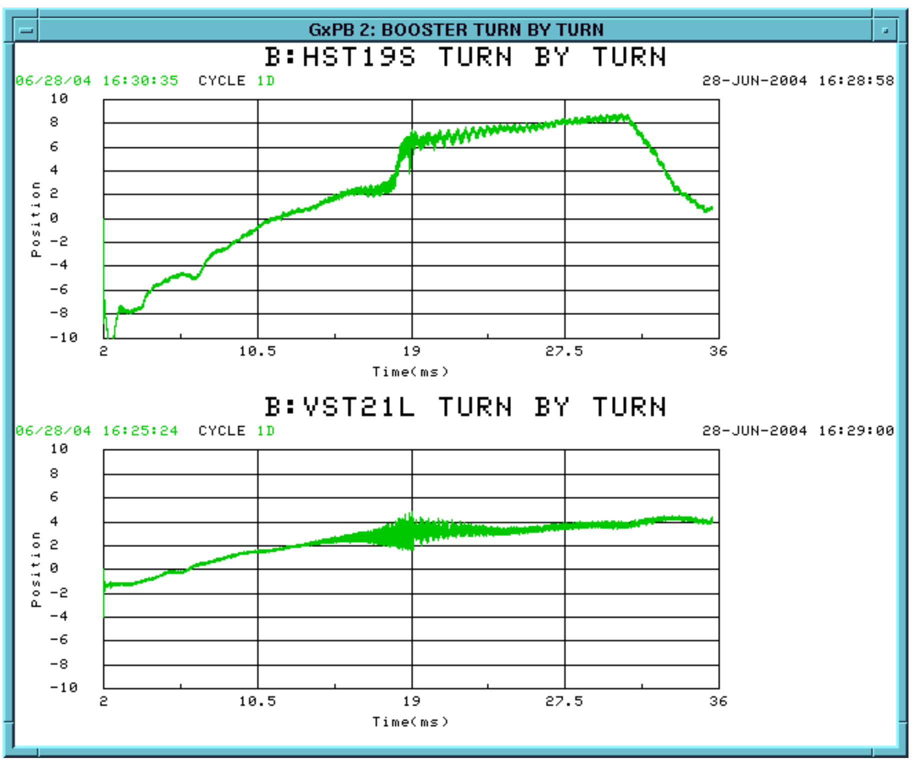



Fig. III.1.2 The most extreme cases of motion throughout the cycle.

It appears from these pictures that a reasonable specification would be 1 cm of beam motion at high field and a slew rate of 1mm/ms up to the middle of the cycle.
*Note :: The existing horizontal trims can produce an 11mm local bump at 8 Gev assuming the 1st and 3rd trims of the bump are run all the way to 10 amps. This is not normally possible because the trims*

*usually have a several amp DC bias. The vertical 3 bump can make about 4mm at 8 Gev under the same conditions.*

### III.2 Tune

Figure III.2.2 shows the horizontal and vertical tunes throughout the cycle. In addition to being able to stabilize the tunes, we have considered halo removal schemes in which we shift the tune near a resonance in one plane or the other.

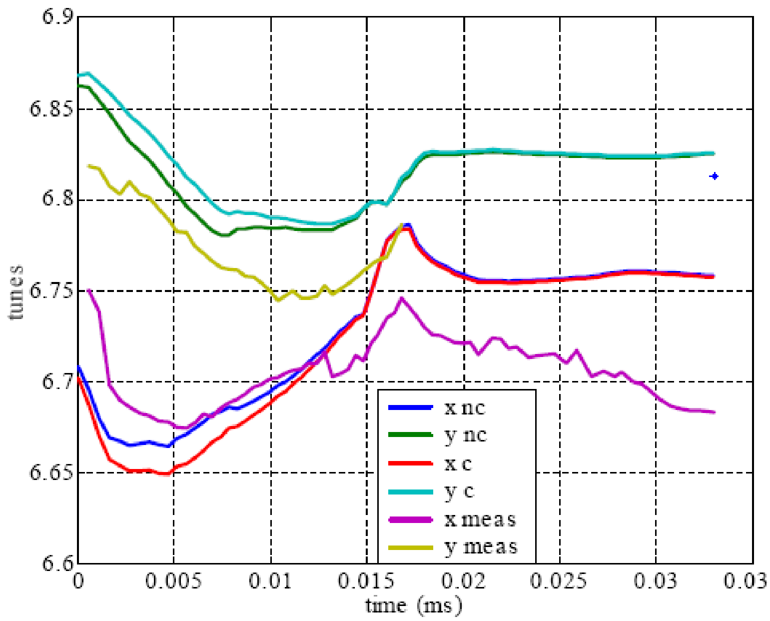



Figure III.2.2: Calculated and measured tunes

From this, it appears that a reasonable specification would be ±0.1 tune control at the high field, with a 0.01 unit/ms maximum slewing rate at all energies.

## IV. Magnetic Field Specifications

### IV.1 Trim Dipoles

The majority of the beam motion is controlled at the high-β regions. The maximum horizontal and vertical β are 33 m and 20 m respectively. There are roughly 100 degrees of phase advance between high-β regions in both planes. The maximum bend angle needed to make a specified lateral deflection in a three-bump occurs at the end correctors and is given by:

$$\Delta x_2 = \theta_1 \sqrt{\beta_1 \beta_2} \sin\psi_{12} = \theta_{max} \beta_{max} \sin\psi_{period}$$

So a maximum deflection of 1cm would require bend angles of

- 0.3 mrad in the horizontal plane
- 0.5 mrad in the vertical plane

The top momentum in the Booster is about 9 GeV/c, at which these angles correspond to 0.009 and 0.015 T-m respectively. The specification of 1 mm/ms up to roughly half way through the cycle corresponds to about 0.5 and 0.8 T-m/s, respectively. Operational requirements to quickly set the dipole field to an initial ramp level at the beginning of a Booster cycle requires a higher slew rate. The recommendation has been made to be able to slew to within 80% of full scale (either positive or negative) of the current corrector dipoles within 2 ms. This brings the field slew rate specification up to 3.6 T-m/s for the horizontal dipole and 6.0 T-m/s for the vertical dipole.

## IV.2 Quadrupoles

The quadrupoles are driven by the requirement that the system be able induce a +/- 0.3 and +/- 0.2 unit tune shift at the highest fields for the horizontal and vertical planes, respectively. This will take a higher field for the lower-β vertical plane. Using the formula

$$\Delta \nu = N \cdot \frac{1}{4\pi} \frac{\beta_{\max}}{f}$$

Where N (=24) is the number of correctors, for the horizontal plane we get

$$f = N \cdot \frac{1}{4\pi} \cdot \frac{\beta_{x,\,max}}{\Delta \nu} = (24) \cdot \frac{1}{4\pi} \cdot \frac{33.7}{0.3} = 214\, m$$

and for the vertical plane

$$f = N \cdot \frac{1}{4\pi} \cdot \frac{\beta_{y,\,max}}{\Delta \nu} = (24) \cdot \frac{1}{4\pi} \cdot \frac{20}{0.2} = 191\, m$$

For the most demanding requirement in the vertical plane, a field strength of 0.16 T-m/m is required to achieve the focal length at the highest momentum.

From operating experience, the desired maximum slew rate for the existing quadrupoles at transition is 4000 Amp/Sec. The existing quadrupole can only respond with 1/3 this slew rate. From the 1970 Booster document FN-206 we see that this 4000 Amp/Sec rate results in a field slew rate of 0.088 Tesla-m/m/millisecond. Hence it is desired that the new corrector power supplies and magnets be able to achieve this field slew rate of 88.0 Tesla-m/m/s.

## IV.3 Skew Quadrupoles

The current skew quadrupoles are sufficient. The text of TM-0405 and the table of strengths disagree. We adopt the stronger of the two, the value from the text of 0.008 T-m/m. We take the same relative slew rate as for the normal trim quadrupoles and ask for 0.8 T-m/m/s.

## IV.4 Sextupoles

The existing sextupole system is sufficient.

The 12 current horizontal sextupoles have a transfer constant of $14.9\times10^{-3}$ T-m/m$^2$/A each and a maximum current of 100 A, for a total integrated B" of 17.8 T-m/m$^2$. To match that with 24 packages, the individual magnets need to produce B"L = 0.75 T-m/m$^2$.

The 9 current vertical sextupoles have a transfer constant of $37.5\times10^{-3}$ T-m/m$^2$/A and a maximum current of 100 A, for a total integrated B" of 33.8 T-m/m$^2$. To match that with 24 packages, the individual magnets need to produce B"L = 1.4 T-m/m$^2$.

The design of the new system is controlled by the vertical sextupoles at 1.4 T-m/m$^2$. We want to be able to switch the sextupoles from full field plus to full field minus in ~1.2 ms or 2350 T-m/m$^2$/sec. This comes from a need to rapidly switch chromaticity at transition time during acceleration. If this is not achievable then they should be as fast as reasonably possible.

*Note: The current specification requires that all magnets be powered independently. It is conceivable the skew quads and sextupoles could be powered in groups to go after certain resonances and that would save some money on power supplies. This however presumes that we know ahead of time exactly which resonances and we do not. To evaluate the beam physics requirement for the skew quadrupole and skew sextupole elements, and determine if all need to be powered would require much more information about the Booster than we are able to learn before hand under the time and operating constraints we have. Independently powered elements provides the maximum flexibility for tuning and will allow us to tune on "any" offending (up to 3rd order) resonance that we chose. Grouping the Sextupoles would also be difficult given the higher slew rate requirements. The supply voltage specification would be very high. The skew quadrupole power supplies are the least expensive and the effort to group these would not result in a relatively large a cost savings.*

# V. Magnet Mechanical Specifications

## V.1 Aperture

The existing corrector packages attach around the standard 4.5" (115 mm) outer diameter beam pipe at <u>all</u> of the straights.

At injection, at a Short Straight a 40π-mm-mR beam width is ~72 mm. The good field region should be ~ 50% larger than that or about 110mm or "guess what" about 4.5". This may be a tough requirement to meet. Within that region we will aim to keep the field uniform to 0.5%, though 1.0% is probably sufficient.

## V.2 Exterior Dimensions

The overall dimensions of the corrector magnet package is expected to be 17 inches long, 16.625 inches high, and 17 inches wide

## VI Summary of Magnet Specifications

The following tables are taken from "Booster Corrector 3D Analysis" by V.S. Kashikhin, October 19, 2005, FNAL Technical Division. Adjustments have been made to the listed maximum slew rates in Table VI.1. Table VI.1 is a summary of the magnet field requirements. Table VI.2 are the estimated parameters and capabilities of the prototype package design. Table VI.3 summarizes the relationship between the fields in the designed magnets and the currents necessary to produce these fields.

Table VI.1 Specified integrated magnet fields and slew rates.

| Type | Integrated field/gradient | Max slew rate |
|---|---|---|
| Horizontal dipole | 0.009 T-m | 3.24 T-m/s |
| Vertical dipole | 0.015 T-m | 3.24 T-m/s |
| Normal quadrupole | 0.16 T | 88 T/s |
| Skew quadrupole | 0.008 T | 0.8 T/s |
| Normal sextupole | 1.41 T/m | 2350T/m/s |
| Skew sextupole | 1.41 T/m | 2350T/m/s |

Table VI.2 The estimated parameters and capabilities of the prototype package design

| Type | Integrated field / gradient | Aperture field / gradient | Eff. length, m | Current, A | Number of turns | DC Resistance, Ohm | Inductance, mH |
|---|---|---|---|---|---|---|---|
| Horizontal dipole | 0.0157 T-m | 0.0357 T | 0.44 | 38.1 | 208 | 0.315 | 14 |
| Vertical dipole | 0.0157 T-m | 0.0357 T | 0.44 | 38.1 | 208 | 0.315 | 14 |
| Normal quadrupole | 0.176 T | 0.49 T/m | 0.36 | 64.8 | 128 | 0.105 | 2.2 |
| Skew quadrupole | 0.0115 T | 0.031 T/m | 0.37 | 2.7 | 168 | 1.68 | 4.0 |
| Normal sextupole | 2.0 T/m | 5.87 T/$m^2$ | 0.34 | 39.8 | 132 | 0.263 | 2.5 |
| Skew sextupole | 2.0 T/m | 5.87 T/$m^2$ | 0.34 | 39.8 | 132 | 0.263 | 2.5 |

Table VI.3 Predicted relationship between magnet currents and fields.

| **Type** | **Integrated field / gradient** | **Aperture field / gradient** | **Current, A** |
|---|---|---|---|
| Horizontal dipole | 0.009 T-m | 0.02 T | 23 |
| Vertical dipole | 0.015 T-m | 0.0357 T | 37 |
| Normal quadrupole | 0.16 T | 0.45 T/m | 60 |
| Skew quadrupole | 0.008 T | 0.021 T/m | 2 |
| Normal sextupole | 1.41 T/m | 4.1 T/$m^2$ | 30 |
| Skew sextupole | 1.41 T/m | 4.1 T/$m^2$ | 30 |

# VII. Power Supply Specifications

## VII.1 Electrical Specifications

Given the magnetic field requirements and the predicted and measured inductances and resistances of the various magnets, the current and voltage requirements of the power supplies are determined. Table VII.1.1 summarizes the computation of these currents and voltages. The values in red are the values measured on the first prototype corrector package (July 2006). Table VII.1.2 lists power supply specification which the different supplies hold in common.

Table VII.1.1 Summary of Booster corrector specifications. The black values are from estimates of the magnet parameters and field strength specifications. The red values are from measurements taken on the first prototype.

**Booster Corrector Specifications**

| | | | | From [1] | | From [2] and **[3]** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Inductance of Magnet** | **Resistance of Magnet** | **Cable Resistance, 200 ft, #8** | **Maximum Integrated Field** | **Field Units** | **Current Corresponding to Max Integ Field** | **Conversion Amps to Field** | **Max Field Slew** | **Min Slew Interval** | **Max Field Slew Rate** | **Current Slew Rate** | **Peak Amplifier Voltage** |
| | **Henries** | **Ohms** | **Ohms** | | | **Amps** | **Amp/(field)** | **(field)** | **Seconds** | **(field)/Sec** | **Amp/Sec** | **Output V** |
| **H-dipole** | 0.014 | 0.315 | 0.308 | 0.0090 | T-m | 23 | 2555.56 | 0.00648 | 0.002 | 3.24 | 8280 | 130.25 |
| | **0.013** | **0.270** | | | | **24.4** | **2710.03** | | | | **8781** | **128.24** |
| **V-dipole** | 0.014 | 0.315 | 0.308 | 0.0150 | T-m | 37 | 2466.67 | 0.00648 | 0.002 | 3.24 | 7992 | 134.94 |
| | **0.013** | **0.270** | | | | **40.4** | **2695.42** | | | | **8733** | **136.90** |
| **N-Quad** | 0.0022 | 0.105 | 0.308 | *0.1600* | T | 60 | 375.00 | 0.088 | 0.001 | 88 | 33000 | 97.38 |
| | **0.0020** | **0.087** | | | | **64** | **397.93** | | | | **35018** | **95.18** |
| **S-Quad** | 0.0040 | 1.68 | 2 | 0.0080 | T | 2 | 250.00 | | | 0.8 | 200 | 8.16 |
| | **0.0042** | **1.18** | | | | **2.01** | **250.75** | | | | **200.6** | **7.22** |
| **N-Sext** | 0.0025 | 0.263 | 0.308 | 1.4100 | T-m/m^2 | 30 | 21.28 | 2.82 | 0.0012 | 2350 | 50000 | 142.13 |
| | **0.0023** | **0.205** | | | | **30.9** | **21.94** | | | | **51559** | **134.46** |
| **S-Sext** | 0.0025 | 0.263 | 0.308 | 1.4100 | T-m/m^2 | 30 | 21.28 | 2.82 | 0.0012 | 2350 | 50000 | 142.13 |
| | **0.0023** | **0.205** | | | | **30.5** | **21.64** | | | | **50854** | **132.62** |

References


[1] Eric Prebys, Jim Lackey, Dave Harding, "Booster Corrector System Specification", November 3, 2004

[2] V.S. Kashikhin, "Booster Corrector 3D Analysis", October 19, 2005

[3] Measurements made on the first prototype by Phil Schlabach and Sasha Makarov

Table VII.1.2 More amplifier specifications.

| Supply Parameter | Value | Units |
|---|---|---|
| Reference Input Voltage Range | +/-10 | Volts |
| Minimum Reference Input Impedance | 20,000 | Ohms |
| Current Regulation (Accuracy) | +/- 2.0 | % |
| Current Regulation (Repeatability) | +/- 1.0 | % |
| Maximum Current Ripple | +/- 1.0 | Amps |
| Settling Time to Within +/- 250 mA | 0.25 | milli-Second |
| Operating Temperature Range | 0 to 35 | degC |

NOTE: The settling time is measured from the end of the ramp for a ramp from 0 to +/- Full Scale Amps and the maximum ramp slope of the particular supply.

## VII.2 Remote Monitoring and Control

Besides the +/-10 Volt reference input, the power amplifiers need to have the following remote monitoring and control features.

Current Monitor : +/- 1V per 10 Amps, or +/- 1V per 5 Amps.
Voltage Monitor : +/- 1V per 20 V
Remote Enable : TTL or contact closure.
Remote Inhibit : TTL or contact closure.

Status Outputs :

- Output Enabled
- Amplifier Normal
- Amplifier Fault
- Over Voltage
- Over-Current
- Over-Temperature

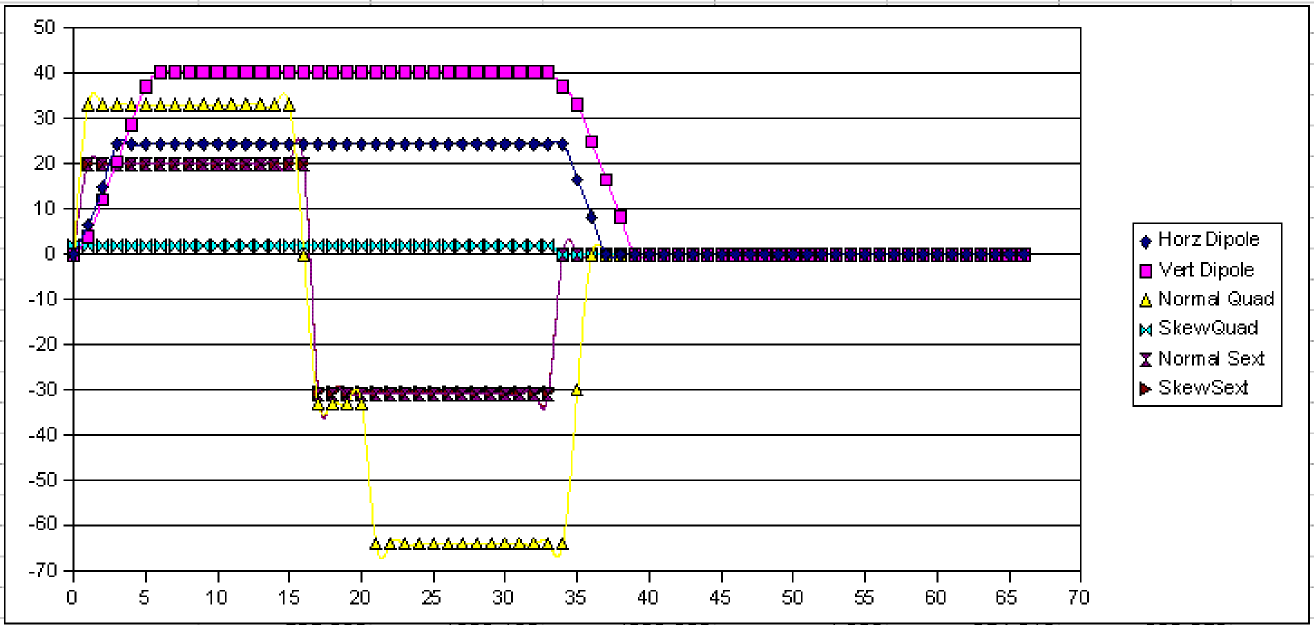
Amplifier Protection :

- Input reference voltage limiter
- Over-Temperature Shutdown
- Over-Current Shutdown
- Over-Voltage Shutdown
- Under-Voltage Shutdown

## VII.3 Bounds on the Corrector Ramps and Power

Figure V11.3.1 is taken from a spreadsheet used to compute electrical power requirements and magnet cooling requirements given bounds on the absolute amplitude of the magnet ramps. The waveforms are assumed to repeat at a 15 Hz rate. The individual RMS currents for each magnet type is useful in determining the gauge of the power cables. The Total Watts value is used in determining the rating of the bulk high voltage supplies that source the amplifiers. The Total Watts Heat in the Magnet value is used in sizing the magnet cooling necessary.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 200ft Cable Res | 0.308 | 0.308 | 0.308 | 2.000 | 0.308 | 0.308 | | |
| Coil Res | 0.270 | 0.270 | 0.087 | 1.180 | 0.205 | 0.205 | | |
| Amps rms | 17.127 | 27.832 | 34.324 | 1.425 | 18.379 | 18.209 | | |
| (Amps rms)^2 * R | 169.539 | 447.741 | 465.363 | 6.455 | 173.285 | 170.088 | 1432.472 | <---Total Watts |
| (Amps rms)^2 * Rcoil | 79.196 | 209.152 | 102.498 | 2.395 | 69.246 | 67.969 | 530.457 | <---Total Watts Heat in Magnet |
| | Horz Dipole | Vert Dipole | Normal Quad | Skew Quad | Normal Sext | Skew Sext | | |
| | Amps^2 | Amps^2 | Amps^2 | Amps^2 | Amps^2 | Amps^2 | | |
| | 0.000 | 0.000 | 0.000 | 4.000 | 0.000 | 0.000 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| | 595.360 | 1632.160 | 4096.000 | 4.000 | 954.810 | 930.250 |

Figure VII.3.1 Power computations given bounds on the corrector magnet ramps.

## VII.4 Installation Requirements

The power amplifiers for the corrector magnet packages will be installed in relay racks located in 6 locations around the Booster accelerator. The power amplifiers in each location will power 8 of the 6 element packages. That is 48 power amplifiers per location.

The power amplifiers and associated bulk power supplies for each location must fit into 4 relay racks. The relay rack dimensions are 78” high x 17” wide x 28” deep.

Figure VII.4.1 is a layout estimate for the case where the 231HC amplifiers from Copley are used for five of the six different supplies. Figure VII.4.2 is a layout estimate for the case where the Fermilab switch-mode power supplies are used to drive the correctors.

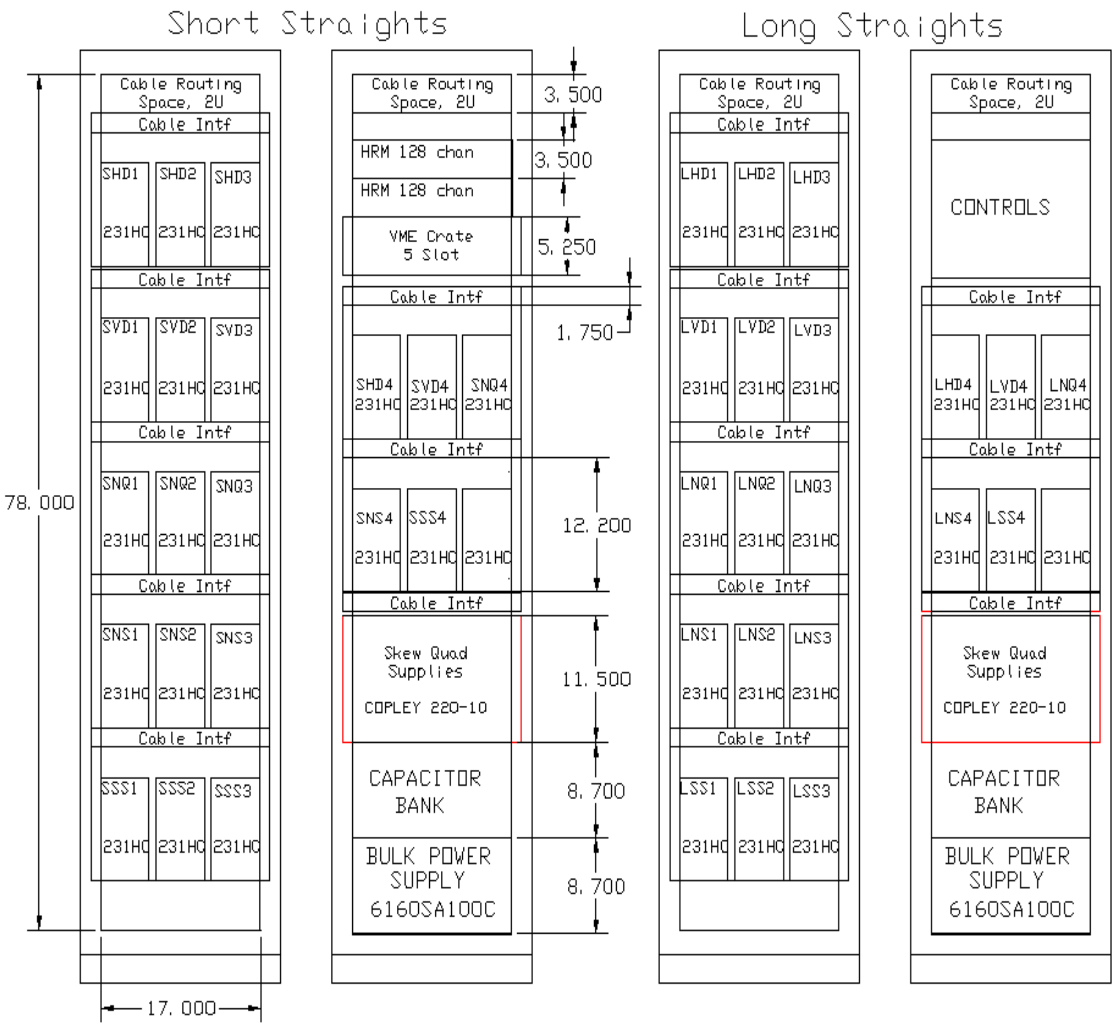



Figure VII.4.1  Rack layout estimate using Copley amplifiers.

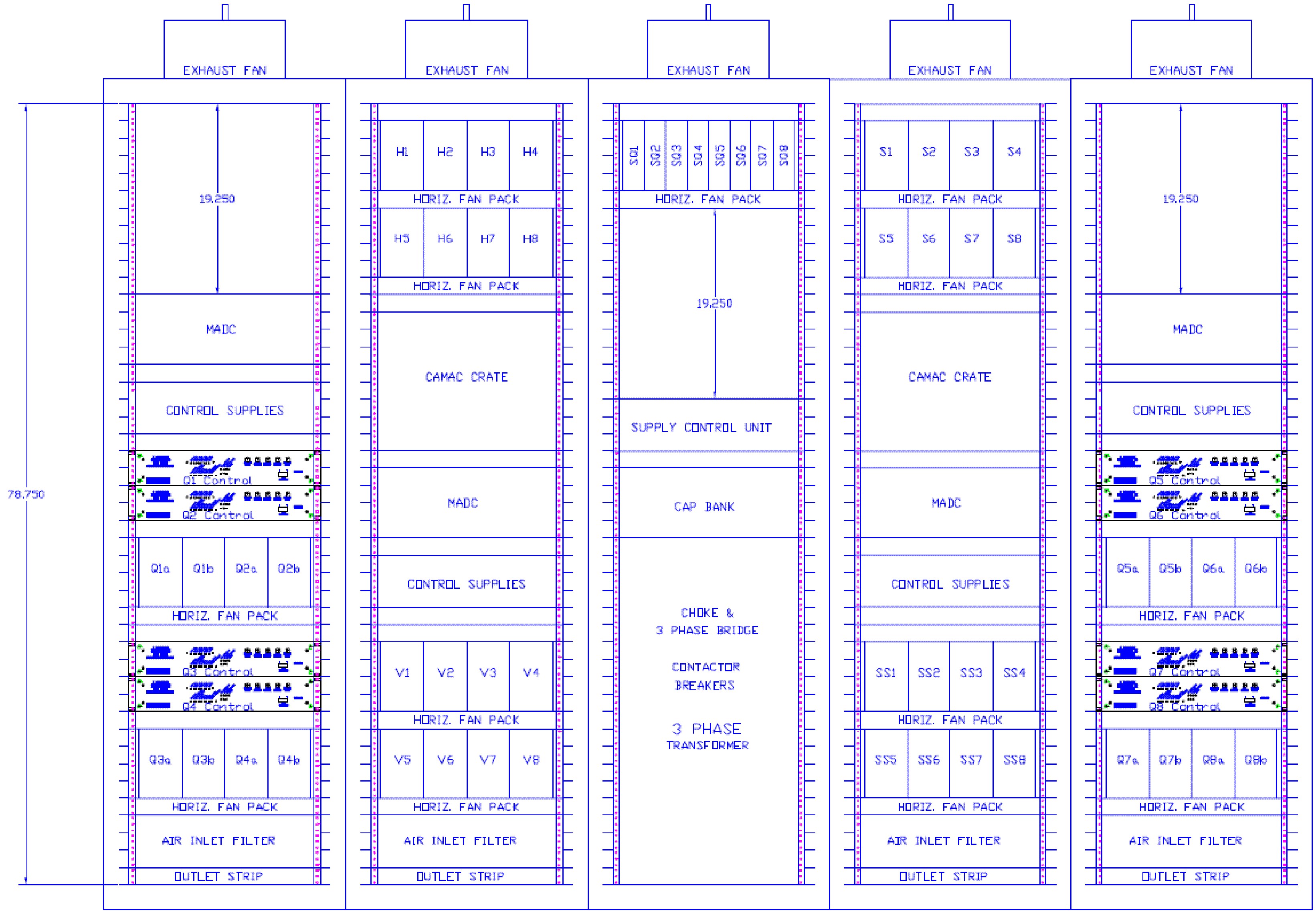



Figure VII.4.2 Rack layout estimate using Fermi switch-mode power supplies.

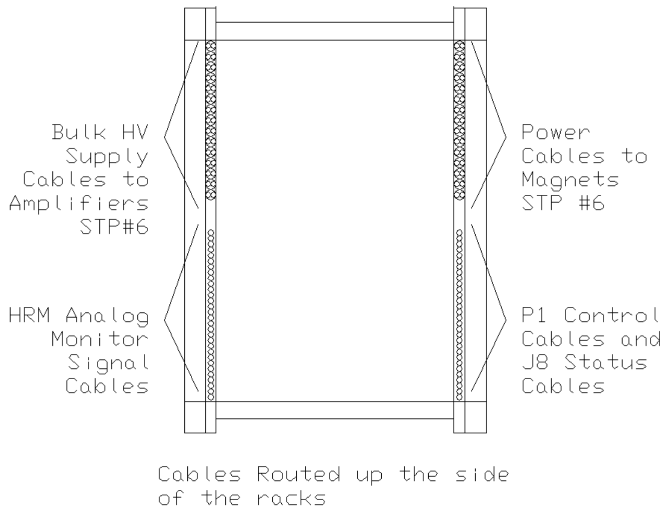



Figure VII.4.3  Top view of the rack showing cables routed up the sides of the rack frame

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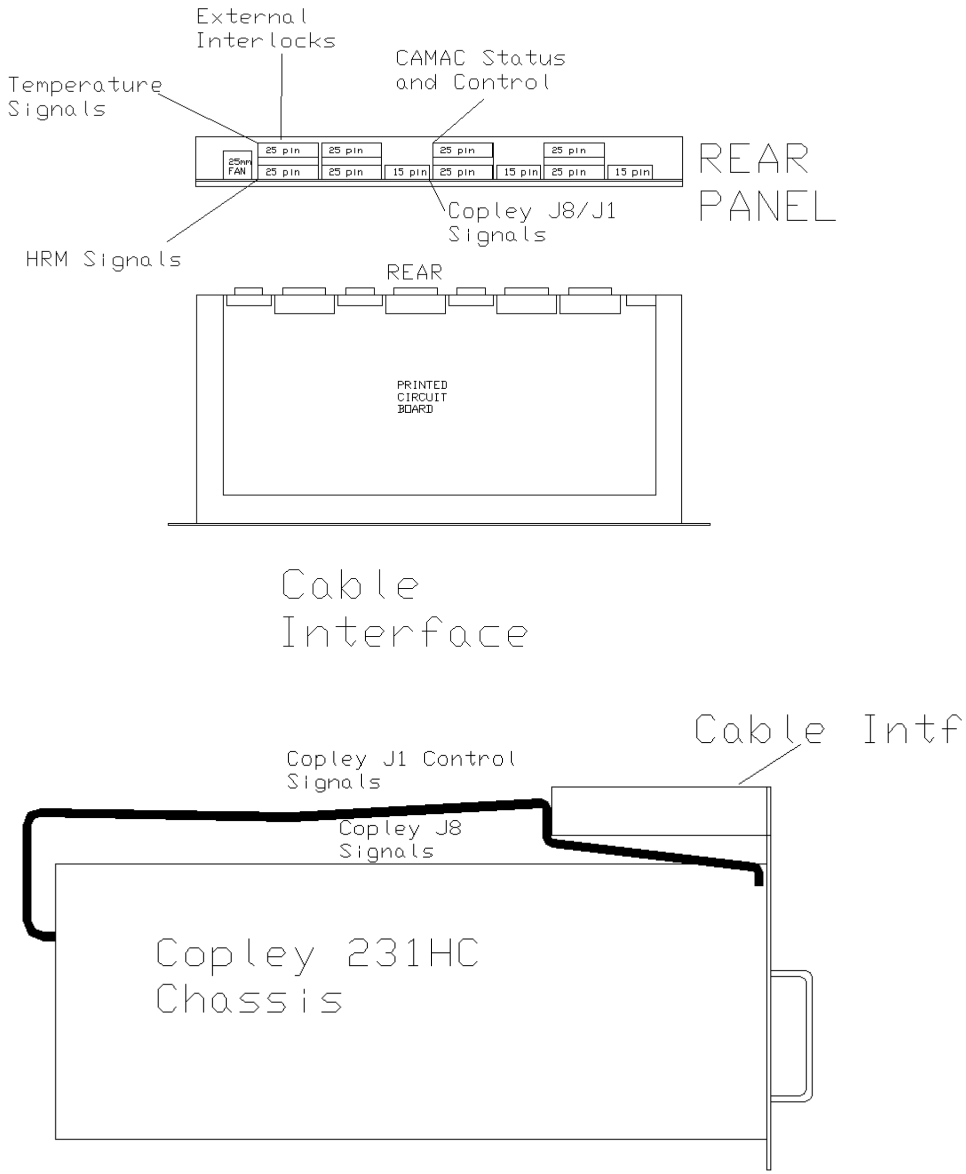


Figure VII.4.4  Illustration of the Cable Interface used to manage signals between the amplifiers and the Controls and Diagnostics.